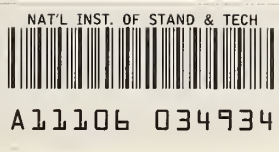
Reference
NBS
PUBLICATIONS



NBSIR 85-3167

Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings

David D. Evans
David W. Stroup

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Gaithersburg, MD 20899

February 1985

Issued July 1985

Prepared for the Sponsor:
U.S. Nuclear Regulatory Commission
Washington, DC 20555

QC
100
.U56
85-3167
1985

NATIONAL BUREAU
OF STANDARDS
LIBRARY

NBS-REF
QC
100
.U56
85-3167
1985
C.1

NBSIR 85-3167

METHODS TO CALCULATE THE RESPONSE TIME OF HEAT AND SMOKE DETECTORS INSTALLED BELOW LARGE UNOBSTRUCTED CEILINGS

David D. Evans
David W. Stroup

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Gaithersburg, MD 20899

February 1985

Issued July 1985

Prepared for the Sponsor:
U.S. Nuclear Regulatory Commission
Washington, DC 20555

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

TABLE OF CONTENTS

		Page
	Abstract	1
1.0	Introduction	1
2.0	Detector Response to t^2 - Fires	4
3.0	Detector Response to Arbitrary Fires	9
4.0	Smoke Detector Response	11
5.0	Summary	15
6.0	Acknowledgement	15
7.0	References	15
8.0	Notation	17
	Appendix A - DETACT - T2 CODE	19
	1) Example Calculation	
	2) Program Listing	
	Appendix B - DETACT - QS CODE	32
	1) Example Calculation	
	2) Program Listing	

METHODS TO CALCULATE THE RESPONSE TIME OF HEAT AND SMOKE DETECTORS INSTALLED BELOW LARGE UNOBSTRUCTED CEILINGS

Abstract

Recently developed methods to calculate the time required for ceiling mounted heat and smoke detectors to respond to growing fires are reviewed. A computer program that calculates activation times for both fixed temperature and rate of rise heat detectors in response to fires that increase in heat release rate proportionally with the square of time from ignition is given. This program produces nearly equivalent results to the tables published in Appendix C, Guide for Automatic Fire Detector Spacing, (NFPA 72E, 1984). A separate method and corresponding program are provided to calculate response time for fires having arbitrary heat release rate histories. This method is based on quasi-steady ceiling layer gas flow assumptions. Assuming a constant proportionality between smoke and heat released from burning materials, a method is described to calculate smoke detector response time, modeling the smoke detector as a low temperature heat detector in either of the two response time models.

1. INTRODUCTION

Studies of the response of heat detectors to fire driven flows under unconfined ceilings have been conducted since the early 1970's [1, 2, 3, 4]. Results of these largely experimental studies have been used to develop correlations of data that are useful under a broad range of fire conditions and building geometries. These correlations have been used to construct engineering methods to determine heat detector spacing, sprinkler response time, and smoke detector alarm times for industrial buildings where large undivided

ceilings over storage and manufacturing facilities are common. The method for calculation of heat detector spacing has been adopted by the National Fire Protection Association (NFPA) as an alternate design method published in the standard NFPA 72E, 1984 [5].

Although the NFPA heat detector spacing calculation is a well documented method, it is not in a convenient form for use by the Nuclear Regulatory Commission (NRC) in evaluating the response characteristics of existing systems for two reasons. 1) Currently, the only available form of the information is the tabular form published in the NFPA 72E standard. An analytic form or computer subroutine that produced equivalent answers would be more flexible and of greater use to NRC. 2) The published tables are organized to look-up spacing requirements for a given response time. In the evaluation of existing systems, the opposite problem is of interest - for a given spacing and detector determine the response time.

As part of this study, the basis for the calculation method published in Appendix C of the NFPA 72E standard was determined. Alternative correlations of the same experimental data that are the basis for the tables in Appendix C of the NFPA 72E standard were used to construct a FORTRAN program (DETACT-T2 Code) to evaluate the response time of existing heat detector systems. Using the program, calculated values for response time agree to within 5 percent of those published in the tables contained in Appendix C of the NFPA 72E standard. Although this calculation method is the most firmly based of those to be discussed in this report, it is restricted to application in which the fire to be detected increases in energy release rate proportionally with the square of time from the ignition.

A separate program (DETACT-QS Code), written in PC BASIC, is capable of evaluating detector response for a fire with an arbitrary energy release rate history. The only restriction is that the energy release rate must be represented as a series of connected straight lines, the end points of which are entered as user input data. Inaccuracies may be introduced in the analysis of rapidly varying fires because this code uses a quasi-steady approximation for the fire driven gas flow. This means that changes at the fire source immediately affect the gas flows at all distances from the fire. In reality, time is required for the gases to travel from the fire to remote locations. Generally, fire driven flows have a velocity the order of one meter per second. Thus a quasi-steady analysis for locations close to the fire will only be in error by a few seconds, while remote locations can be delayed by tens of seconds. Keeping this approximation in mind, this program represents the most flexible of available methods but has not been tested against experimental data.

Both of the codes discussed above analyze detector response at installation sites under large unconfined ceilings. For smaller compartments, in which confining walls will cause a layer of fire products to accumulate under the ceiling, hence submerging the ceiling-jet flow before the heat detector can respond, different calculations are necessary. The problem of analyzing the response of heat detectors or sprinklers in a two-layer environment (warm fire products over cool air) has been studied [6], but no single code has been produced to facilitate analysis. This class of problem will not be discussed in this report.

Analysis of smoke detector response is currently performed by approximating the smoke detector as a low-temperature zero-lag-time heat detector. Selection of the response temperature corresponding to a given detector sensitivity also depends on the relative proportion of "smoke" and energy released by the burning fuel. Test data of gas temperature rise at the time of smoke detector alarm is presented in this report. An alternative approximate method is given to determine this same temperature rise by using fuel smoke and energy release rate measurements obtained in a laboratory scale apparatus developed by Tewarson [7].

2. DETECTOR RESPONSE TO t^2 - FIRES

Appendix C of the NFPA 72E standard [5], "Guide for Automatic Fire Detector Spacing," contains methods to determine the required heat detector spacing that will provide alarms to growing fires before the fire has grown to a user specified energy release rate. Tables provide information to evaluate different fire growth rates, ceiling heights, ambient temperatures, detector alarm conditions (fixed temperature or rate of rise), and detector thermal time constant. The tables reflect the extensive experimental studies and mathematical fire modeling performed by Heskestad and Delichatsios at Factory Mutual Research Corporation [3, 4].

Beyler [8] uses a different correlation of Heskestad and Delichatsios' data than was used to produce the tables in NFPA 72E Appendix C to obtain an analytical expression for the gas flow temperature and velocity produced under ceilings that can be used to evaluate heat detector response. Beyler's solutions are limited to evaluation of fires that increase in energy release rate

proportionally with the square of time from ignition. This class of fire is commonly referred to as a "t-squared-fire." Briefly, the problem of the heat detector response is solved using analytic solutions for the time dependent temperature of the detector sensing element up to the point when it is heated to the specified alarm conditions. The model for the detector sensing element temperature is based on a convective heat transfer process. Characterization of the thermal response of heat detector and sprinkler thermal sensing elements is discussed by Heskestad and Smith [9], and Evans [10]. The first order differential equation that describes the rate of temperature increase of the sensing element is [6]:

$$\frac{dT_s}{dt} = \frac{U^{1/2}}{RTI} \left[T - T_s \right] \tag{1}$$

The notation for all equations is given in the notation section. The value of RTI (Response Time Index), a measure of the thermal time constant of the detector, is determined by testing [9]. Values of the time-dependent gas temperature and velocity are obtained from the following correlations [8].

$$\Delta T_2^* = 0 \quad \text{for } t_2^* < (t_2^*)_f$$

$$\Delta T_2^* = \{[t_2^* - 0.954(1 + r/H)]/[0.188 + 0.313\ r/H]\}^{4/3} \quad \text{for } t_2^* > (t_2^*)_f$$

$$(t_2^*)_f = 0.954\ [1 + r/H] \tag{2}$$

$$U_2^* = 0.59\ [r/H]^{-0.63} [\Delta T_2^*]^{1/2}$$

where

$$U_2^* = U/[A\ \alpha\ H]^{1/5}$$

$$\Delta T_2^* = \Delta T/[A^{2/5}(T_\infty/g)\ \alpha^{2/5}\ H^{-3/5}]$$

$$t_2^* = t/[A^{-1/5}\ \alpha^{-1/5} H^{4/5}]$$

$$A = g/(c_p T_\infty \rho_\infty)$$

$$\Delta T = T - T_\infty$$

$$\alpha = t^2/Q$$

The solutions to equation (1) for detector sensing element temperature, T_s, and rate of temperatue rise, dT_s/dt, in response to the t^2 - fire with growth rate specified by the value of α are from Beyler [8] as follows:

$$\Delta T_s = (\Delta T/\Delta T_2^*)\ \Delta T_2^*\ [1 - (1 - e^{-Y})/Y] \tag{3}$$

$$\frac{dT_s}{dt} = \frac{(4/3)(\Delta T/\Delta T_2^*)(\Delta T_2^*)^{1/4}}{(t/t_2^*)(0.188 + 0.313\ r/H)}\ (1 - e^{-Y}) \tag{4}$$

where

$$Y = \frac{3}{4}\ \frac{U}{U_2^*}^{1/2}\ \frac{U_2^*}{\Delta T_2^*}^{1/2}\ \frac{\Delta T_2^*}{RTI}\ \frac{t}{t_2^*}\ (0.188 + 0.313\ r/H)$$

assuming that $\Delta T_s = 0$ initially. T and U in equation 1 are obtained from the correlations in equation set (2) for ΔT_2^* and U_2^* respectively. Equations 3 and 4 were programmed into a user interactive FORTRAN code called the DETACT-T2

Code. This code solves for the time required to reach a specified positive value of ΔT_s or dT_s/dt representing detector alarm. Details of the DETACT-T2 Code use, a worked example, and program listing are given in Appendix A. Briefly for a fixed temperature detector, the user enters values for:

Ambient air temperature

Detector response temperature or rate of temperature rise

Detector RTI

Fuel to ceiling distance

Radial distance of detector from the fire plume axis

Fire growth rate constant α (for t^2 fires)

Outputs of the code are the time to detector response and fire energy release rate at that time.

In Appendix A, use of the DETACT-T2 Code to calculate the response time of a fixed temperature detector is demonstrated in a worked example using the following program inputs:

Ambient air temperature	21.1°C (70°F)
Detector response temperature	54.44°C (130°F)
Detector RTI	370.34 $m^{1/2}s^{1/2}$ (670.8 $ft^{1/2}s^{1/2}$)
Fuel to ceiling distance	3.66 m (12 ft.)
Radial distance of detector from axis of fire	2.16 m (7.07 ft.)
Fire growth rate constant	11.71 J/s^3 (0.0111 BTU/s^3)

The calculated response time using the DETACT-T2 Code is 298 seconds and corresponding fire energy release rate is 1.04 MW (986 BTU/s). This same fire and detector combination can be seen in the table C-3-2.1.1(e) in Appendix C of NFPA 72E [5], (in the table notation, threshold fire size 1000 BTU/s, fire growth rate, medium; DET TC = 300 Δ s, $\Delta T = 60^0F$, ceiling height = 12 Δft, installed spacing in the body of the table 10ft). All values in table C-3-2.1.2(e) [5] are for detector response times of 300 seconds. This is in agreement with the 298 s calculated with the DETACT-T2 Code given in Appendix A of this report.

Eleven other randomly selected combinations of fires and detectors were calculated using the DETACT-T2 Code and results compared to table values in Appendix C of NFPA 72E [5]. Of these cases the greatest deviation was 7.5% and least was 0.17%.

Use of the DETACT-T2 Code has two main advantages over the tables in Appendix C of NFPA 72E [5]. One is that the code is specifically designed to evaluate existing facilities. The other is that any t^2 - fire growth rate can be analyzed. The tables in Appendix C of NFPA 72E [5] contain only three different fires. At present, an NBS special publication is being prepared containing tabular results with the same information as those in the NFPA 72E, Appendix C [5], but recast into a form useful for evaluation of existing facilities. This publication "Evaluating Thermal Fire Detection Systems," by Stroup, Evans, and Martin should become available in 1986.

3. DETECTOR RESPONSE TO ARBITRARY FIRES

The DETACT-T2 Code is useful for evaluating the response of specified detectors to t^2 - fire growth rates. In some cases a fire of interest does not follow an energy release rate that is proportional to the square of time from ignition. For these cases use of the DETACT-T2 Code to evaluate the responses of detector systems is inappropriate.

To evaluate detector response to an arbitrary energy release rate history, an assumption of quasi-steady gas flow temperatures and velocities is made. With this assumption, correlation for ceiling-jet temperatures and velocities obtained from experiments using steady fire energy release rate sources can be used to evaluate growing fires. The growing fire is represented in the calculation as a series of steady fires with energy release rates changing in time to correspond to the fire of interest.

Correlations of ceiling-jet temperatures and velocities from experiments using steady fire sources have been published by Alpert [1]. Recast into metric form they are:

$$\Delta T = 16.9\, Q^{2/3}/H^{5/3} \qquad \text{for} \quad r/H < 0.18$$

$$U = 0.95\, (Q/H)^{1/3} \qquad \text{for} \quad r/H < 0.15 \qquad (5)$$

$$\Delta T = 5.38(Q/r)^{2/3}/H \qquad \text{for} \quad r/H > 0.18$$

$$U = 0.2\, Q^{1/3}\, H^{1/2}/r^{5/6} \qquad \text{for} \quad r/H > 0.15$$

where the metric units are T[°C], U[m/s], Q[kW], r[m], H[m].

A computer code to perform the integration of equation 1, the differential equation for detector sensor temperature, using the quasi-steady fire driven flow approximation and Alpert's correlations from equations in 5, is listed in Appendix B. This code, called the DETACT-QS Code, is written in PC BASIC. The code requires user input similiar to the DETACT-T2 Code in Appendix A, with the one exception that the fire energy release rate is specified as a series of time, energy release rate data pairs.

The same fire and detector case used as an example of execution for the DETACT-T2 Code was evaluated using the DETACT-QS Code. The example inputs and results are given in Appendix B. The fire was input as time, energy release rate pairs at intervals of 5 seconds to match the t^2 - fire with α = 11.7105 W/s^2. Other parameters were maintained the same. The resulting predicted detection time using the DETACT-QS Code was 313 seconds with the corresponding fire energy release rate at detection of 1147 kW. Remember that with the DETACT-T2 Code the calculated time of detection was 298 seconds with fire energy release rate at detection of 1040 kW. This example was chosen to demonstrate specifically that there will be differences between the two methods even in the evaluation of the same fire. The quasi-steady fire analysis on which the DETACT-QS Code is based has the advantage that arbitrary fire energy release rates can be input as a data set.

4. SMOKE DETECTOR RESPONSE

Both of the heat detector response models discussed are based on predictions of the temperature and velocity of the fire driven gas flow under the ceiling and models of the heat detector response. The same calculations could be used to predict smoke detector response given a relationship between smoke concentration and temperature rise in the fire driven gas flow and the response characteristics of the smoke detector.

The response characteristics of smoke detectors are not as well understood as thermal detectors. Smoke detector alarm conditions depend on more than smoke concentration. Smoke particle sizes and optical or particle scattering properties can affect the value of smoke concentration necessary to reach alarm conditions. For thermal detectors, measured values of RTI characterize the lag time between gas temperature and sensing element temperature. For smoke detectors there is no analogous method to characterize the lag time between gas flow smoke concentration and the smoke concentration within the sensing chamber. In the absence of understanding of the many processes affecting smoke detector response, a smoke detector will be considered to be a low temperature heat detector with no thermal lag, i.e. RTI = 0. The analogy between smoke obscuration in the gas flow and temperature rise will be developed in order to determine the corresponding temperature rise to use as a model for a smoke detector known to alarm at a given smoke obscuration.

Similarity between temperature rise and smoke concentration will be maintained everywhere within a fire-driven flow if the energy and smoke continuity equations are similar. For the case of constant c_p, k, and D these equations are:

$$\rho c_p \frac{d\Delta T}{dt} - k \nabla^2 \Delta T = \dot{Q}''' \tag{6}$$

$$\rho \frac{dY_s}{dt} - \rho D \nabla^2 Y_s = \dot{m}''' \tag{7}$$

If the Lewis number $k/\rho c_p D = 1$, then the ratio of temperature rise to smoke concentration can remain constant throughout the fire driven flow, if the ratio $\dot{Q}'''/c_p \dot{m}_s'''$ is maintained constant in all regions where energy is exchanged with the flow. Reactions in the flame over the burning fuel will determine the ratio of temperature rise to smoke concentration throughout the flow. Other energy exchanges in normal fire flows, convection to cool room boundaries, and radiation from smokey gases decrease the ratio of temperature rise to smoke concentration because energy is extracted from the flow without a proportional decrease in smoke concentration. Mixing of hot combustion products with cool smokey gases that may accumulate in an enclosure also decrease the ratio of temperature rise to smoke concentration because smoke mass is added to the flow without a proportional increase in energy. For fire driven flows in which the effects that alter the ratio of temperature rise to smoke concentration are not significant, the response of smoke detectors may be calculated as if it were a fixed temperature heat detector. The temperature rise necessary for alarm of this substitute heat detector is calculated from the product of smoke concentration needed to alarm the smoke detector and the ratio of temperature rise to smoke concentration produced by the burning material.

Generally the sensitivity of smoke alarms are given in terms of the amount of obscuration by the smokey flow that is necessary to produce an alarm and not directly in smoke concentration. The more sensitive the smoke detector the smaller the amount of obscuration needed to alarm.

The obscuring ability of a smoke laden gas flow is measured by the attenuation of a light beam. The measure of the attenuation is the optical density per unit beam length, OD, [3]

$$OD = \left(\log_{10} \frac{I_o}{I}\right)/L \tag{8}$$

By testing, Seader and Einhorn [11] found that the attenuating abilities of smokes produced from many different materials undergoing flaming combustion were similar. For flaming combustion they found that the optical density per unit length was proportional to the mass concentration of "smoke" in a gas flow as:

$$OD = 3330 \quad C_s \tag{9}$$

where OD is optical density per meter and C_s is smoke mass concentration in kilograms per cubic meter.

The ratio of temperature rise in a fire driven flow to smoke concentration may be recast in terms of optical density using equation 9 as:

$$\frac{\Delta T}{Y_s} = \frac{\rho \Delta T}{C_s} = \frac{3330 \rho \Delta T}{OD} \tag{10}$$

Under the assumption discussed at the beginning of this section, this ratio will be equal to the ratio $\dot{Q}'''/c_p \dot{m}_s'''$. The last ratio may be approximated by a volume average over the combustion region so that

$$\frac{3330 \rho \Delta T}{OD} = \frac{\dot{Q}}{c_p \dot{m}_s}$$

or

$$\frac{OD}{\Delta T} = \frac{3330 \rho c_p \dot{m}_s}{\dot{Q}} \qquad (11)$$

As an example, literature values for oak wood may be used to obtain a representative value. For oak

$\dot{Q}$ = 7600 kJ/kg fuel consumed per unit time [12]

$\dot{m}_s$ = 0.017 kg smoke/kg fuel consumed per unit time [12]

air c_p = 1 kJ/kg°C

air ρ = 1.165 kg/m^3 at 30°C

From equation (11) $\frac{OD}{\Delta T} = 8.68 \times 10^{-3}$ $(m^0C)^{-1}$.

Heskestad and Delichatsios [3] have reported representative optical density per meter for smoke detector alarm and corresponding temperature rise in the gas flow. For wood crib (unknown type) fires, the ratio of these values was $OD/\Delta T = 1.2 \times 10^{-3}$ [1/m°C]. This is the same order of magnitude as the number calculated in the analysis given above and may be representative of the expected accuracy given no knowledge of wood type. Heskestad and Delichatsios [3] report that an ionization detector will alarm in response to a wood fire at OD = 0.016 1/m.

Using the $OD/\Delta T$ value for wood of $1.2 \times 10^{-3}(m°C)^{-1}$ the corresponding change in gas temperature would be 13°C, $(0.016/1.2 \times 10^{-3})$. For the purpose of response time calculation using the heat detector models, this ionization smoke detector would be represented as a low temperature heat detector alarming at 13°C above ambient for a wood fire.

Other measurements of the ratio $OD/\Delta T$ are obtained for burning materials in a laboratory scale apparatus developed by Tewarson [7]. Values for a large number of plastics and wood under many environmental conditions are given by Tewarson [12].

5. SUMMARY

Two methods have been presented to calculate the response of heat detectors installed under large unobstructed ceilings in response to growing fires. Smoke detector response is calculated using the same thermal calculations by approximating the smoke detector as a low temperature, zero lag time thermal detector.

6. ACKNOWLEDGMENT

The authors are grateful to Mr. Doug Walton for coding DETACT-QS version 1.1 for exection in PC BASIC.

7. REFERENCES

1. Alpert, R.L., Calculation of response time of ceiling-mounted fire detectors. Fire Technology, 8, 1972, p 181.

2. Alpert, R.L., Turbulent ceiling-jet induced by large-scale fires, Combustion Science and Technology, 11, 1975, p 197.

3. Heskestad, G. and Delichatsios, M.A., Environments of fire detectors phase 1; Effects of fire size, ceiling height and material, Volume II - Analysis. Technical Report Serial No. 22427, RC 77-T-11, Factory Mutual Research Corporation, Norwood Massachusetts 02062, 1977.

4. Heskestad, 6, and Delichatsios, M.A., The initial convective flow in fire, Seventeenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pennsylvania, 1978, pp 1113-1123.

5. Standard on Automatic Fire Detectors, NFPA 72E-1984, Appendix C, National Fire Protection Association, Batterymarch Park, Quincy, MA, 02269.

6. Evans, D.D., Calculating Sprinkler Actuation Time in Compartment, to be published in Fire Safety Journal, 1985.

7. Tewarson, A., and Pion, R., "A Laboratory-Scale Test Method for the Measurement of Flammability Parameters, FMRC serial No. 22524, Factory Mutual Research Corporation, Norwood, Mass. 02062, Oct 1977.

8. Beyler, C.L., A design method for flaming fire detection,Fire Technology, 20, 4, 1984, p 5.

9. Heskestad, G., Smith, H., Investigation of a New Sprinkler Sensitivity Approval Test: The Plunge Test FMRC Technical Report 22485, Factory Mutual Research Corporation, Norwood, Mass. 02062, 1976.

10. Evans, D.D., Madrzykowski, D., Characterizing the Thermal Response of Fusible-Link Sprinklers, NBSIR 81-2329, U.S. Department of Commerce, National Bureau of Standards, Washington, D.C. 20234, (1981).

11. Seader, J. and Einhorn, I., "Some Physical, Chemical, Toxicological, and Physiological Aspects of Fire Smokes", Sixteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Penn. 1976, pp 1423-1445.

12. Tewarson, A., Physico-Chemical and Combustion/Pyrolysis Properties of Polymeric Materials. FMRC J.I. OEONG.RC, Factory Mutual Research Corporation, Norwood, Mass 02062, Nov. 1980, p 27.

8. NOTATION

A	$g/(c_p \ T_\infty \ \rho_\infty)$
c_p	specific heat capacity of ambient air
C_s	smoke mass concentration
D	effective Binary diffusion coefficient
g	acceleration of gravity
H	vertical distance from fuel to ceiling
I	light intensity
I_o	initial Light intensity
L	light beam length
$\dot{m}_s'''$	smoke gas mass production rate per unit volume
OD	optical density per unit length (see eq. 8)
$\dot{Q}$	fire energy release rate
$\dot{Q}'''$	energy release rate per unit volume.
r	radial distance from fire axis to the detector
RTI	response time index, the product of the detector thermal time constant and the square root of the gas speed used in the test to measure the time constant [9].
t	time
t_2^*	dimensionless time $t/[A^{-1/5}\alpha^{-1/5}H^{4/5}]$
$(t_2^*)_f$	dimensionless time for time delay for gas front travel.
T_∞	ambient temperature
T	gas temperature at detector location
T_s	temperature of detector sensing elements
ΔT	$T - T_\infty$
ΔT_2^*	dimensionless temperature difference $\Delta T/[A^{2/5}(T_f/g)\ \alpha^{\ 2/5}H^{-3/5}]$
U	gas speed at the detector location
U_2^*	dimensionless gas speed $U/[A\ \alpha\ H]^{1/5}$

Y_s	local ratio of smoke mass to total mass in flow
α	proportionality constant for t^2- fire growth = Q/t^2
ρ_∞	ambient air density

APPENDIX A - DETACT-T2 CODE

FORTRAN Program to Calculate Detector Response to t^2 - Fires

1) Example Calculation

2) Program Listing

APPENDIX A. DETACT-T2 CODE

A FORTRAN Program to Calculate Detector Response to t^2 - Fires

This appendix describes the theory and use of a computer program which determines the response of fixed temperature and rate of rise heat detectors to fires with energy release rates described by the expression $Q = \alpha t^2$. The program is designed for use in evaluating detectors installed at known spacings.

The activation time of a given detector is a function of fire growth rate, ceiling height, detector spacing, detector activation temperature, ambient temperature, and detector response time index (RTI). The program prompts the user to provide this information. These input data are converted to a dimensionless form for use in the calculations. Equations for the activation time of a fixed temperature detector and a rate of rise detector are set up. The two equations are then solved using a Newton-Raphson technique. Once the activation times are known, the fire energy release rates at those times are calculated. Finally, the results for each detector type are printed as well as some appropriate input data.

In the following example, input prompts from the computer program are printed in all capital letters while user responses are printed in lower case (where possible) and proceeded by the character ">".

EXAMPLE

Calculate the activation times for fixed temperature and rate of rise heat detectors installed, using a 3.05 meter spacing, in an area with a ceiling height of 3.66 meters. The detectors have an RTI of 370.3 $(m\text{-}sec)^{1/2}$. The detector activation temperature is 54.4°C, and the activation rate of rise is 8.33°C/min. Ambient temperature is 21°C.

```
ENTER 1 FOR ENGLISH UNIT INPUT
      2 FOR METRIC UNIT INPUT
>2
ENTER THE AMBIENT TEMPERATURE IN DEGREES C.
>21
ENTER THE DETECTOR RESPONSE TIME INDEX (RTI) IN (M-SEC)**1/2.
>370.3
ENTER THE DETECTOR ACTIVATION TEMPERATURE IN DEGREES C.
>54.4
ENTER A DETECTOR RATE OF RISE IN DEGREES C/MIN.
>8.33
ENTER THE CEILING HEIGHT IN METERS.
>3.66
ENTER THE DETECTOR SPACING IN METERS.
>3.05
ENTER:  S FOR SLOW FIRE GROWTH RATE
        M FOR MEDIUM FIRE GROWTH RATE
        F FOR FAST FIRE GROWTH RATE OR
        O FOR OTHER
>m
```

RESULTS:

CEILING HEIGHT = 3.66 METERS (12.0 FEET)

DETECTOR SPACING = 3.05 METERS (10.0 FEET)

DETECTOR RTI = 370.3 (M-SEC)**1/2 (670.8 (FT-SEC)**1/2)

FIRE GROWTH CONSTANT = .1171+002 WATTS/SEC**2)
(.1111-001 BTU/SEC**3)

FOR TEMPERATURE ACTUATED DETECTOR:

ACTIVATION TEMPERATURE = 54.4 DEGREES C (129.9 DEGREES F)

TIME OF ACTIVATION = 297.88 SECS

HEAT RELEASE RATE = .1038+007 WATTS (.9840+003 BTU/SEC)

FOR RATE OF RISE ACTUATED DETECTOR:

ACTIVATION RATE OF RISE = 8.33 DEGREES C/MIN
(14.99 DEGREES F/MIN)

TIME OF ACTIVATION = 182.75 SECS

HEAT RELEASE RATE = .3908+006 WATTS (.3704+003 BTU/SEC)

The results show that the heat detector would activate approximately 298 seconds after the fire reaches a flaming state. The heat release rate at this time would be 1038 kilowatts. A rate of rise detector would activate at about 183 seconds with a corresponding heat release rate of 391 kilowatts.

If English units had been selected, the input requests would have called for data in English units instead of metric units.

The program is written in ANSI 77 FORTRAN. A PC BASIC version is being coded. Each is in a form which makes it easy to incorporate into existing computer fire models as a subroutine.

```
****** PROGRAM DETACT-12 ******

      PROGRAM DETACT
C
C*****************************************************************
C
C            DETACT-12 CODE
C
C A FORTRAN PROGRAM FOR CALCULATING DETECTOR RESPONSE
C TO TIME SQUARED FIRES.
C
C*****************************************************************
C
C*****************************************************************
C
C THIS IS A PROGRAM FOR CALCULATING ACTIVATION TIME AND HEAT
C RELEASE RATE FOR A GIVEN DETECTOR. THE PROGRAM CALCULATES RESULTS
C FOR BOTH TEMPERATURE AND RATE OF RISE ACTUATED DETECTORS. THE
C PROGRAM REQUIRES DATA DESCRIBING THE DETECTOR, ROOM, AND FIRE
C CHARACTERISTICS.
C
C PROGRAM WRITTEN BY D. W. STROUP      1/4/85
C FINAL REVISION 1/9/85
C
C*****************************************************************
C
C====>  VERSION 1.0  <=================================
C
C INPUT:
C   J      - UNITS CODE  (1 OR 2)
C            1 - INPUT DATA IN ENGLISH UNITS
C            2 - INPUT DATA IN METRIC UNITS
C   TAMB   - AMBIENT TEMPERATURE
C   RTI    - DETECTOR RESPONSE TIME INDEX
C   TACT   - DETECTOR ACTIVATION TEMPERATURE
C   ROR    - DETECTOR ACTIVATION RATE OF RISE
C   HF     - CEILING HEIGHT
C   ZF     - DETECTOR SPACING
C   M      - GROWTH FACTOR CODE, CHARACTER VARIABLE  (S, M, F, OR 0)
C   ALPHA  - FIRE GROWTH RATE FACTOR
C            IF M = 0, ALPHA SHOULD CONTAIN THE GROWTH FACTORR TO BE USED.
C            IF M <> 0, ALPHA MAY BE SET TO ZERO.
C
C OUTPUT:
C   T      - TIME OF ACTIVATION FOR A TEMPERATURE DETECTOR
C   QD     - HEAT RELEASE RATE AT TIME OF ACTIVATION, T
C   TR     - TIME OF ACTIVATION FOR RATE OF RISE DETECTOR
C   QDR    - HEAT RELEASE RATE AT TIME OF ACTIVATION, TR
C   IERR   - ERROR CODE  (0 OR 1)
C            0 - SUCCESSFUL
C            1 - UNSUCCESSFUL
C
C*****************************************************************
C
      CHARACTER M
      DATA IRITY,IWITY/5,6/
      DATA GE,CPE,RHOE/32.2,0.24,0.0735/
      DATA GM,CPM,RHOM/9.8,1.0035,1.1768/
      IERR=0
```

```
****** PROGRAM DETACT-T2 ******

      WRITE (IWTTY,10)
10    FORMAT (' ENTER: 1 FOR ENGLISH UNIT INPUT'/19,'2 FOR METRIC UNIT I
     &NPUT')
      READ (IRTTY,*) J
      IF (J.EQ.1) THEN
      WRITE (IWTTY,20)
20    FORMAT (' ENTER THE AMBIENT TEMPERATURE IN DEGREES F.')
      READ (IRTTY,*) TAMB
      WRITE (IWTTY,30)
30    FORMAT (' ENTER THE DETECTOR RESPONSE TIME INDEX (RTI) IN (FT-SEC)
     &**1/2.')
      READ (IRTTY,*) RTI
      IF (RTI.LT.0.000001) RTI=0.000001
      RTIR=RTI
      WRITE (IWTTY,40)
40    FORMAT (' ENTER THE DETECTOR ACTIVATION TEMPERATURE IN DEGREES F.'
     &)
      READ (IRTTY,*) TACT
      WRITE (IWTTY,50)
50    FORMAT (' ENTER A DETECTOR RATE OF RISE IN DEGREES F/MIN.')
      READ (IRTTY,*) ROR
      WRITE (IWTTY,60)
60    FORMAT (' ENTER THE CEILING HEIGHT IN FEET.')
      READ (IRTTY,*) HF
      WRITE (IWTTY,70)
70    FORMAT (' ENTER THE DETECTOR SPACING IN FEET.')
      READ (IRTTY,*) ZF
      WRITE (IWTTY,80)
80    FORMAT (' ENTER: S FOR SLOW FIRE GROWTH RATE'/
     &                 M FOR MEDIUM FIRE GROWTH RATE'/
     &                 F FOR FAST FIRE GROWTH RATE OR'/
     &                 0 FOR OTHER ')
      READ (IRTTY,410) M
      IF ((M.EQ.'s').OR.(M.EQ.'S')) ALPHA=0.00277778
      IF ((M.EQ.'m').OR.(M.EQ.'M')) ALPHA=0.0111111
      IF ((M.EQ.'f').OR.(M.EQ.'F')) ALPHA=0.0444445
      IF (M.NE.'0') GO TO 100
      WRITE (IWTTY,90)
90    FORMAT (' ENTER THE FIRE GROWTH RATE CONSTANT (ALPHA) IN BTU/SEC/S
     &EC/SEC.')
      READ (IRTTY,*) ALPHA
100   CONTINUE
      ELSE
      WRITE (IWTTY,110)
110   FORMAT (' ENTER THE AMBIENT TEMPERATURE IN DEGREES C.')
      READ (IRTTY,*) TAMB
      WRITE (IWTTY,120)
120   FORMAT (' ENTER THE DETECTOR RESPONSE TIME INDEX (RTI) IN (M-SEC)*
     &*1/2.')
      READ (IRTTY,*) RTI
      IF (RTI.LT.0.000001) RTI=0.000001
      RTIR=RTI
      WRITE (IWTTY,130)
130   FORMAT (' ENTER THE DETECTOR ACTIVATION TEMPERATURE IN DEGREES C.'
     &)
      READ (IRTTY,*) TACT
      WRITE (IWTTY,140)
140   FORMAT (' ENTER A DETECTOR RATE OF RISE IN DEGREES C/MIN.')
```

```
****** PROGRAM DETACT-12 ******

      READ (IRTTY,*) ROR
      WRITE (IWTTY,150)
150   FORMAT (' ENTER THE CEILING HEIGHT IN METERS.')
      READ (IRTTY,*) HF
      WRITE (IWTTY,160)
160   FORMAT (' ENTER THE DETECTOR SPACING IN METERS.')
      READ (IRTTY,*) ZF
      WRITE (IWTTY,80)
      READ (IRTTY,410) M
      IF ((M.EQ.'s').OR.(M.EQ.'S')) ALPHA=2.930555556
      IF ((M.EQ.'m').OR.(M.EQ.'M')) ALPHA=11.72222222
      IF ((M.EQ.'f').OR.(M.EQ.'F')) ALPHA=46.8888889
      IF (M.NE.'0') GO TO 180
      WRITE (IWTTY,170)
170   FORMAT (' ENTER THE FIRE GROWTH RATE CONSTANT (ALPHA) IN WATT/SEC/
     &SEC.')
      READ (IRTTY,*) ALPHA
180   CONTINUE
      END IF
C
C ************************ CALCULATIONS ********************************
C
      R=0.5*SQRT(2.)*ZF
      ROH=R/HF
      ROR=ROR/60.
      IF (J.EQ.1) THEN
      TAMB=TAMB+460.
      TACT=TACT+460.
      A=GE/(CPE*TAMB*RHOE)
      G=GE
      ELSE
      TAMB=TAMB+273.
      TACT=TACT+273.
      A=GM/(CPM*TAMB*RHOM*1000.)
      G=GM
      END IF
      TOTS2=A**(-1./5.)*ALPHA**(-1./5.)*HF**(4./5.)
      DLTODL=A**(2./5.)*(TAMB/G)*ALPHA**(2./5.)*HF**(-3./5.)
      UOUS2=A**(1./5.)*ALPHA**(1./5.)*HF**(1./5.)
      DELTD=TACT-TAMB
      IF (ROH.GT.0.3) THEN
      UODLTH=0.59*ROH**(-0.63)
      ELSE
      UODLTH=3.87/(9.115**0.5)
      ENDIF
      TS2F=0.954*(1.+ROH)
      A2=(4./3.)*DLTODL*UOUS2**(-0.5)*UODLTH**(-0.5)*RTI/
     &          (TOTS2*(0.188+0.313*ROH))
      C=1.0+DELTD/A2
      CALL NWTN (C,Y,IERR,IWTTY)
      IF (IERR.EQ.1) GO TO 380
      DELTS2=(4./3.)*UOUS2**(-0.5)*UODLTH**(-0.5)*RTI*Y/
     &                (TOTS2*(0.188+0.313*ROH))
      TS2=0.954*(1.+ROH)+(0.188+0.313*ROH)*DELTS2**(3./4.)
      TS2=TS2+TS2F
      T=TS2*A**(-1./5.)*ALPHA**(-1./5.)*HF**(4./5.)
      QD=ALPHA*T**2
      IF (RTIR.LE.2.0) RTIR=2.0
```

```
****** PROGRAM DETACT-T2 ******

      D1=(4./3.)*DLTODL/(TOTS2*(0.188+0.313*ROH))
      D2=(3./4.)*UOUS2**0.5*UODLTH**0.5*(1./RTIR)*TOTS2
     &                *(0.188+0.313*ROH)
      CALL BISECT (D1,D2,ROR,DELTS2,IERR,IWTTY)
      IF (IERR.EQ.1) GO TO 380
      TS2R=0.954*(1.+ROH)*(0.188+0.313*ROH)*DELTS2**(3./4.)
      TS2R=TS2R+TS2F
      TR=TS2R*A**(-1./5.)*ALPHA**(-1./5.)*HF**(4./5.)
      QDR=ALPHA*TR**2
C
C ****** PRINT OUT RESULTS ***********************************************
C
      ROR=ROR*60.
      WRITE (IWTTY,190)
190   FORMAT ('1  RESULTS:')
      IF (J.EQ.1) THEN
      HF2=HF*0.3048
      ZF2=ZF*0.3048
      WRITE (IWTTY,200) HF,HF2,ZF,ZF2
200   FORMAT ('0    CEILING HEIGHT    = ',F6.2,' FEET (',F6.2,' METERS)'/
     &          16,'DETECTOR SPACING = ',F6.2,' FEET (',F6.2,' METERS)')
      RTI2=RTI*(0.3048**0.5)
      WRITE (IWTTY,210) RTI,RTI2
210   FORMAT ('0    DETECTOR RTI = ',F6.1,' (FT-SEC)**1/2 (',F6.1,' (M-S
     &EC)**1/2)')
      ALPHA2=ALPHA*1055.
      WRITE (IWTTY,220) ALPHA,ALPHA2
220   FORMAT ('0    FIRE GROWTH CONSTANT = ',E12.4,' BTU/(SEC**3)'/
     &                                    (',E12.4,' WATTS/SEC**2)')
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      WRITE (IWTTY,230)
230   FORMAT (//'0  FOR TEMPERATURE ACTUATED DETECTOR:')
      TACT=TACT-460.
      TACT2=(5./9.)*(TACT-32.)
      WRITE (IWTTY,240) TACT,TACT2
240   FORMAT ('0    ACTIVATION TEMPERATURE = ',F6.1,' DEGREES F (',F6.1,
     &' DEGREES C)')
      WRITE (IWTTY,250) T
250   FORMAT ('0    TIME TO ACTIVATION = ',F6.2,' SECONDS')
      QD2=QD*1055.
      WRITE (IWTTY,260) QD,QD2
260   FORMAT ('0    HEAT RELEASE RATE = ',E12.4,' BTU/SEC'/
     &                                  (',E12.4,' WATTS)')
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      WRITE (IWTTY,270)
270   FORMAT (//'0  FOR RATE OF RISE ACTUATED DETECTOR:')
      ROR2=ROR*(5./9.)
      WRITE (IWTTY,290) ROR,ROR2
290   FORMAT ('0    ACTIVATION RATE OF RISE = ',F6.2,' DEGREES F/MIN (',
     &                F6.2,' DEGREES C/MIN)')
      WRITE (IWTTY,250) TR
      QDR2=QDR*1055.
      WRITE (IWTTY,260) QDR,QDR2
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      ELSE
```

```
      HF2=HF*(1./0.3048)
      ZF2=ZF*(1./0.3048)
      WRITE (IWTTY,300) HF,HF2,ZF,ZF2
300   FORMAT ('0    CEILING HEIGHT    = ',F6.2,' METERS (',F6.2,' FEET)'/
     &          '0,'DETECTOR SPACING = ',F6.2,' METERS (',F6.2,' FEET)')
      RTI2=RTI*((1./0.3048)**0.5)
      WRITE (IWTTY,320) RTI,RTI2
320   FORMAT ('0    DETECTOR RTI = ',F6.1,' (M-SEC)**1/2 (',F6.1,' (FT-S
     &EC)**1/2)')
      ALPHA2=ALPHA*(1./1055.)
      WRITE (IWTTY,330) ALPHA,ALPHA2
330   FORMAT ('0    FIRE GROWTH CONSTANT = ',E12.4,' WATTS/(SEC**2)'/
     &                                    ('  ,E12.4,' BTU/SEC**3)')
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      WRITE (IWTTY,230)
      TACT=TACT-273.
      TACT2=(9./5.)*TACT+32.
      WRITE (IWTTY,340) TACT,TACT2
340   FORMAT ('0    ACTIVATION TEMPERATURE = ',F6.1,' DEGREES C (',F6.1,
     &' DEGREES F)')
      WRITE (IWTTY,350) T
350   FORMAT ('0    TIME TO ACTIVATION = ',F8.2,' SECONDS')
      QD2=QD*(1./1055.)
      WRITE (IWTTY,360) QD,QD2
360   FORMAT ('0    HEAT RELEASE RATE = ',E12.4,' WATTS'/
     &                                  ('  ,E12.4,' BTU/SEC)')
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      WRITE (IWTTY,270)
      ROR2=ROR*(9./5.)
      WRITE (IWTTY,370) ROR,ROR2
370   FORMAT ('0    ACTIVATION RATE OF RISE = ',F6.2,' DEGREES C/MIN (',
     &          F6.2,' DEGREES F/MIN)')
      WRITE (IWTTY,350) TR
      QDR2=QDR*(1./1055.)
      WRITE (IWTTY,360) QDR,QDR2
      WRITE (IWTTY,400)
      READ (IRTTY,410) M
      END IF
      STOP 'PROGRAM COMPLETED'
380   CONTINUE
      WRITE (IWTTY,390)
390   FORMAT (' ********> ERROR IN DETACT ROUTINE <********')
400   FORMAT (//' <RETURN> TO CONTINUE')
410   FORMAT (A1)
      STOP 'PROGRAM ABORTED'
      END
```

```
****** SUBROUTINE NWTN   ******

      SUBROUTINE NWTN (C,P,IERR,IWTTY)
C
C*****************************************************************
C
C  NEWTON-RAPHSON SUBROUTINE
C
C  THIS SUBROUTINE IS USED TO EVALUATE THE TIME EXPRESSION FOR THE
C  FIXED TEMPERATURE DETECTOR.
C
C*****************************************************************
C
      P0=0.1
      TOL=0.00001
      NO=1000
      I=1
      IERR=0
10    CONTINUE
      IF (I.LE.NO) THEN
      IF (P0.GT.50.) THEN
      X=0.0
      ELSE
      X=EXP(-P0)
      END IF
      FX=P0+X-C
      FPMX=1.0-X
      IF (FPMX.LT.0.00000001) GO TO 30
      P=P0-(FX/FPMX)
      IF (ABS(P-P0).LT.TOL) THEN
      IERR=0
      RETURN
      ELSE
      I=I+1
      P0=P
      END IF
      GO TO 10
      END IF
      IERR=1
      WRITE (IWTTY,20) I
20    FORMAT (' NEWTON-RAPHSON FAILED AFTER NO ITERATIONS, NO = ',I4)
      RETURN
30    WRITE (IWTTY,40)
40    FORMAT (' SLOPE OF EQUATION TOO CLOSE TO ZERO FOR '/
     &   '   NEWTON-RAPHSON METHOD.'/
     &   '   ERROR RETURN')
      IERR=1
      RETURN
      END
```

```
****** SUBROUTINE BISECT ******

      SUBROUTINE BISECT (D1,D2,ROR,P,IERR,IWITY)
C
C*****************************************************************
C
C BISECTION SUBROUTINE
C
C THIS SUBROUTINE EVALUATES THE TIME EXPRESSION FOR THE RATE OF
C RISE DETECTOR USING A BISECTION METHOD.
C
C*****************************************************************
C
      IERR=0
      TOL=0.00001
      NO=1000
      A=0.0
      B=1000.0
      RLMT=TOL/20.0
10    CONTINUE
      IF ((D2*B).GT.50.) THEN
      X=0.0
      ELSE
      X=EXP(-D2*B)
      ENDIF
      FXB=D1*B**0.25-D1*B**0.25*X-ROR
      IF (FXB.LT.0.0) THEN
      A=B
      B=B+500.
      GO TO 10
      ENDIF
      I=1
20    CONTINUE
      IF (I.LE.NO) THEN
      P=A+(B-A)/2.0
      IF ((D2*P).GT.50.) THEN
      X=0.0
      ELSE
      X=EXP(-D2*P)
      ENDIF
      FX=D1*P**0.25-D1*P**0.25*X-ROR
      IF (((FX.GT.-RLMT).AND.(FX.LT.RLMT)).OR.(((B-A)/2.).LT.TOL)) THEN
      IERR=0
      RETURN
      ELSE
      I=I+1
      IF ((D2*A).GT.50.) THEN
      X=0.0
      ELSE
      X=EXP(-D2*A)
      ENDIF
      FXA=D1*A**0.25-D1*A**0.25*X-ROR
      IF ((FXA*FX).GT.0.0) THEN
      A=P
      ELSE
      B=P
      ENDIF
      ENDIF
      GO TO 20
```

```
      ENDIF
      IERR=1
      WRITE (IWTTY,30) I
30    FORMAT (' BISECT ROUTINE FAILED AFTER NO ITERATIONS, NO = ',I4)
      RETURN
      END
```

APPENDIX B - DETACT-QS CODE

PC BASIC Program to Calculate

Detector Response to Fire with Arbitrary

Energy Release Rate Histories

1) Example Calculation

2) Program Listing

```
DETACT-QS  VERSION 1.1   WRITTEN BY D.D. EVANS  1985
CONTRIBUTION OF THE NATIONAL BUREAU OF STANDARDS (U.S.).
NOT SUBJECT TO COPYRIGHT.

QUASI-STEADY FIRE CALCULATION OF DETECTOR ACTUATION TIME
BELOW AN UNCONFINED CEILING BASED ON ALPERT'S EQUATIONS
AS PUBLISHED IN FIRE TECHNOLOGY AUGUST 1972.

                    USER SUPPLIED INPUT

HEIGHT OF CEILING ABOVE FUEL (METERS)                ? 3.6576

DISTANCE OF DETECTOR FROM AXIS OF FIRE (METERS)      ? 2.155

INITIAL ROOM TEMPERATURE (CELSIUS)                   ? 21.111

DETECTOR ACTUATION TEMPERATURE (CELSIUS)
(140 F = 60 C   160 F = 71 C   165 F = 74 C)         ? 54.444

DETECTOR RESPONSE TIME INDEX (RTI)  (m*s)^(1/2)      ? 370.34

NEXT A DESCRIPTION OF THE FIRE HEAT RELEASE RATE AS A
AS A FUNCTION OF TIME MUST BE CONSTRUCTED. THIS WILL BE
DONE BY THE USER ENTERING KEY HEAT RELEASE RATES ALONG
THE DESIRED FIRE CURVE. FOR THE USERS INFORMATION THE
MINIMUM HEAT RELEASE RATE NECESSARY TO ACTUATE THE
DETECTOR AT THE LOCATION GIVEN IS 232  kW.


ENTER KEY HEAT RELEASE RATES THAT DETERMINE THE SHAPE OF THE
DESIRED FIRE DEVELOPMENT CURVE.  USUALLY THE FIRST DATA
PAIR WILL BE  ( TIME  0   HEAT RELEASE  0 ). UP TO 100
PAIRS CAN BE ENTERED.  TO STOP ENTERING DATA  ENTER ANY
NEGATIVE TIME VALUE.  THE PROGRAM WILL GENERATE HEAT
RELEASE RATE VALUES BETWEEN THE VALUES ENTERED AS NEEDED
BASED ON A STRAIGHT LINE INTERPOLATION BETWEEN POINTS AT
ONE SECOND INTERVALS


 1 ..   TIME (SEC)        ? 0

        HEAT RELEASE (kW)? 0


 2 ..   TIME (SEC)        ? 5

        HEAT RELEASE (kW)? 0.2928
```

```
3 ..   TIME (SEC)        ? 10
       HEAT RELEASE (kW)? 1.1711

4 ..   TIME (SEC)        ? 15
       HEAT RELEASE (kW)? 2.635

5 ..   TIME (SEC)        ? 20
       HEAT RELEASE (kW)? 4.684

6 ..   TIME (SEC)        ? 25
       HEAT RELEASE (kW)? 7.319

7 ..   TIME (SEC)        ? 30
       HEAT RELEASE (kW)? 10.539

8 ..   TIME (SEC)        ? 35
       HEAT RELEASE (kW)? 14.345

9 ..   TIME (SEC)        ? 40
       HEAT RELEASE (kW)? 18.737

10 ..   TIME (SEC)        ? 45
       HEAT RELEASE (kW)? 23.71

11 ..   TIME (SEC)        ? 50
       HEAT RELEASE (kW)? 29.28

12 ..   TIME (SEC)        ? 55
       HEAT RELEASE (kW)? 35.42

13 ..   TIME (SEC)        ? 60
       HEAT RELEASE (kW)? 42.16
```

```
14 ..   TIME (SEC)        ? 65
       HEAT RELEASE (kW)? 49.48

15 ..   TIME (SEC)        ? 70
       HEAT RELEASE (kW)? 57.38

16 ..   TIME (SEC)        ? 75
       HEAT RELEASE (kW)? 65.87

17 ..   TIME (SEC)        ? 80
       HEAT RELEASE (kW)? 74.95

18 ..   TIME (SEC)        ? 85
       HEAT RELEASE (kW)? 84.61

19 ..   TIME (SEC)        ? 90
       HEAT RELEASE (kW)? 94.86

20 ..   TIME (SEC)        ? 95
       HEAT RELEASE (kW)? 105.69

21 ..   TIME (SEC)        ? 100
       HEAT RELEASE (kW)? 117.11

22 ..   TIME (SEC)        ? 105
       HEAT RELEASE (kW)? 129.11

23 ..   TIME (SEC)        ? 110
       HEAT RELEASE (kW)? 141.70

24 ..   TIME (SEC)        ? 115
       HEAT RELEASE (kW)? 154.87
```

```
25 ..   TIME (SEC)        ? 120
        HEAT RELEASE (kW)? 168.63

26 ..   TIME (SEC)        ? 125
        HEAT RELEASE (kW)? 182.98

27 ..   TIME (SEC)        ? 130
        HEAT RELEASE (kW)? 197.91

28 ..   TIME (SEC)        ? 135
        HEAT RELEASE (kW)? 213.4

29 ..   TIME (SEC)        ? 140
        HEAT RELEASE (kW)? 229.5

30 ..   TIME (SEC)        ? 145
        HEAT RELEASE (kW)? 246.2

31 ..   TIME (SEC)        ? 150
        HEAT RELEASE (kW)? 263.5

32 ..   TIME (SEC)        ? 155
        HEAT RELEASE (kW)? 281.3

33 ..   TIME (SEC)        ? 160
        HEAT RELEASE (kW)? 299.8

34 ..   TIME (SEC)        ? 165
        HEAT RELEASE (kW)? 318.8

35 ..   TIME (SEC)        ? 170
        HEAT RELEASE (kW)? 338.4
```

```
36 ..   TIME (SEC)        ? 175
       HEAT RELEASE (kW)? 358.6

37 ..   TIME (SEC)        ? 180
       HEAT RELEASE (kW)? 379.4

38 ..   TIME (SEC)        ? 185
       HEAT RELEASE (kW)? 400.8

39 ..   TIME (SEC)        ? 190
       HEAT RELEASE (kW)? 422.7

40 ..   TIME (SEC)        ? 195
       HEAT RELEASE (kW)? 445.3

41 ..   TIME (SEC)        ? 200
       HEAT RELEASE (kW)? 468.4

42 ..   TIME (SEC)        ? 205
       HEAT RELEASE (kW)? 492.1

43 ..   TIME (SEC)        ? 210
       HEAT RELEASE (kW)? 516.4

44 ..   TIME (SEC)        ? 215
       HEAT RELEASE (kW)? 541.3

45 ..   TIME (SEC)        ? 220
       HEAT RELEASE (kW)? 556.8

46 ..   TIME (SEC)        ? 225
       HEAT RELEASE (kW)? 592.8
```

```
47 ..   TIME (SEC)        ? 230
       HEAT RELEASE (kW)? 619.5

48 ..   TIME (SEC)        ? 235
       HEAT RELEASE (kW)? 646.7

49 ..   TIME (SEC)        ? 240
       HEAT RELEASE (kW)? 674.5

50 ..   TIME (SEC)        ? 245
       HEAT RELEASE (kW)? 702.9

51 ..   TIME (SEC)        ? 250
       HEAT RELEASE (kW)? 731.9

52 ..   TIME (SEC)        ? 255
       HEAT RELEASE (kW)? 761.5

53 ..   TIME (SEC)        ? 260
       HEAT RELEASE (kW)? 791.6

54 ..   TIME (SEC)        ? 265
       HEAT RELEASE (kW)? 822.4

55 ..   TIME (SEC)        ? 270
       HEAT RELEASE (kW)? 835.7

56 ..   TIME (SEC)        ? 275
       HEAT RELEASE (kW)? 885.6

57 ..   TIME (SEC)        ? 280
       HEAT RELEASE (kW)? 918.1
```

```
58 ..   TIME (SEC)        ? 285
       HEAT RELEASE (kW)? 951.2

59 ..   TIME (SEC)        ? 290
       HEAT RELEASE (kW)? 984.9

60 ..   TIME (SEC)        ? 295
       HEAT RELEASE (kW)? 1019.1

61 ..   TIME (SEC)        ? 300
       HEAT RELEASE (kW)? 1053.9

62 ..   TIME (SEC)        ? 305
       HEAT RELEASE (kW)? 1089.4

63 ..   TIME (SEC)        ? 310
       HEAT RELEASE (kW)? 1125.4

64 ..   TIME (SEC)        ? 315
       HEAT RELEASE (kW)? 1162.0

65 ..   TIME (SEC)        ? 320
       HEAT RELEASE (kW)? 1199.2

66 ..   TIME (SEC)        ? 325
       HEAT RELEASE (kW)? 1236.9

67 ..   TIME (SEC)        ? 330
       HEAT RELEASE (kW)? 1275.3

68 ..   TIME (SEC)        ? 335
       HEAT RELEASE (kW)? 1314.2
```

```
 69 ..   TIME (SEC)        ? 340
        HEAT RELEASE (kW)? 1353.7

 70 ..   TIME (SEC)        ? 345
        HEAT RELEASE (kW)? 1393.8

 71 ..   TIME (SEC)        ? 350
        HEAT RELEASE (kW)? 1434.5

 72 ..   TIME (SEC)        ? 355
        HEAT RELEASE (kW)? 1475.8

 73 ..   TIME (SEC)        ? 360
        HEAT RELEASE (kW)? 1517.7

 74 ..   TIME (SEC)        ? -1
SEND OUTPUT TO PRINTER (Y OR N) ? N

CEILING HEIGHT= 3.6576  RADIUS= 2.155  DET ACT TEMP= 54.444  RTI= 370.34
```

TIME sec	FIRE kW	GAS TEMP C	DET TEMP C
0.0	0.0	21.1	21.1
10.0	1.2	22.0	21.1
20.0	4.7	23.4	21.1
30.0	10.5	25.2	21.2
40.0	18.7	27.1	21.3
50.0	29.3	29.3	21.4
60.0	42.2	31.6	21.6
70.0	57.4	34.0	21.9
80.0	75.0	36.5	22.2
90.0	94.9	39.2	22.6
100.0	117.1	41.9	23.1
110.0	141.7	44.8	23.6
120.0	168.6	47.7	24.2
130.0	197.9	50.8	24.9
140.0	229.5	53.8	25.7
150.0	263.5	57.0	26.6
160.0	299.8	60.3	27.6
170.0	338.4	63.6	28.7
180.0	379.4	67.0	29.8
190.0	422.7	70.4	31.1
200.0	468.4	73.9	32.4

```
     210.0      516.4       77.5       33.9
     220.0      556.8       80.6       35.4
     230.0      619.5       84.8       37.1
     240.0      674.5       88.5       38.8
     250.0      731.9       92.3       40.6
     260.0      791.6       96.2       42.6
     270.0      835.7       99.2       44.6
     280.0      918.1      104.0       46.7
     290.0      984.9      108.0       48.9
     300.0     1053.9      112.0       51.2
     310.0     1125.4      116.1       53.6

       **** DETECTOR ACTUATION AT   313.4 SECONDS ****

TYPE A CARRIAGE RETURN TO CONTINUE?

ANALYZE SAME FIRE WITH DIFFERENT DETECTOR (Y OR N) ? N
```

```
10 DIM S(101),Q(101)
20 K=10
30 PRINT "DETACT-QS  VERSION 1.1   WRITTEN BY D.D. EVANS  1985"
40 PRINT "CONTRIBUTION OF THE NATIONAL BUREAU OF STANDARDS (U.S.)."
50 PRINT "NOT SUBJECT TO COPYRIGHT."
60 PRINT " "
70 PRINT "QUASI-STEADY FIRE CALCULATION OF DETECTOR ACTUATION TIME"
80 PRINT "BELOW AN UNCONFINED CEILING BASED ON ALPERT'S EQUATIONS"
90 PRINT "AS PUBLISHED IN FIRE TECHNOLOGY AUGUST 1972."
100 PRINT " "
110 PRINT " "
120 PRINT "                      USER SUPPLIED INPUT"
130 PRINT " "
140 PRINT "HEIGHT OF CEILING ABOVE FUEL (METERS)                ";
150 INPUT H
160 PRINT " "
170 PRINT "DISTANCE OF DETECTOR FROM AXIS OF FIRE (METERS)      ";
180 INPUT R
190 PRINT " "
200 PRINT "INITIAL ROOM TEMPERATURE (CELSIUS)                   ";
210 INPUT T1
220 PRINT " "
230 PRINT "DETECTOR ACTUATION TEMPERATURE (CELSIUS)"
240 PRINT "(140 F = 60 C   160 F = 71 C   165 F = 74 C)         ";
250 INPUT T9
260 PRINT " "
270 PRINT "DETECTOR RESPONSE TIME INDEX (RTI)  (m*s)^(1/2)      ";
280 INPUT L
290 PRINT " "
300 PRINT "NEXT A DESCRIPTION OF THE FIRE HEAT RELEASE RATE AS A"
310 PRINT "AS A FUNCTION OF TIME MUST BE CONSTRUCTED. THIS WILL BE"
320 PRINT "DONE BY THE USER ENTERING KEY HEAT RELEASE RATES ALONG"
330 PRINT "THE DESIRED FIRE CURVE. FOR THE USERS INFORMATION THE"
340 PRINT "MINIMUM HEAT RELEASE RATE NECESSARY TO ACTUATE THE"
350 PRINT "DETECTOR AT THE LOCATION GIVEN IS";
360 X=((T9-T1)*H/5.38*R^(2/3))^(3/2)
370 IF R/H>.18 THEN 390
380 X=((T9-T1)*H^(5/3)/16.9)^(3/2)
390 X=X+.5
400 X=INT(X)
410 PRINT X;
420 PRINT " kW."
430 PRINT " "
440 PRINT " "
450 PRINT "ENTER KEY HEAT RELEASE RATES THAT DETERMINE THE SHAPE OF THE"
460 PRINT "DESIRED FIRE DEVELOPMENT CURVE.  USUALLY THE FIRST DATA"
470 PRINT "PAIR WILL BE  ( TIME  0   HEAT RELEASE  0 ). UP TO 100"
480 PRINT "PAIRS CAN BE ENTERED.  TO STOP ENTERING DATA  ENTER ANY"
490 PRINT "NEGATIVE TIME VALUE.  THE PROGRAM WILL GENERATE HEAT"
500 PRINT "RELEASE RATE VALUES BETWEEN THE VALUES ENTERED AS NEEDED"
510 PRINT "BASED ON A STRAIGHT LINE INTERPOLATION BETWEEN POINTS AT"
520 PRINT "ONE SECOND INTERVALS"
530 PRINT " "
540 PRINT " "
550 N=1
```

```
560 FOR I=1 TO 101
570 S(I)=1.701412E+38
580 Q(I)=0
590 NEXT I
600 PRINT N;
610 PRINT ".. TIME (SEC) ";
620 INPUT S(N)
630 IF S(N)<0 THEN 710
640 PRINT " "
650 PRINT " HEAT RELEASE (kW)";
660 INPUT Q(N)
670 PRINT " "
680 N=N+1
690 PRINT " "
700 GOTO 600
710 S(N)=S(N-1)+1
720 PR=0
730 PRINT " "
740 PRINT "SEND OUTPUT TO PRINTER (Y OR N) ";
750 INPUT A$
760 IF A$="Y" OR A$="y" THEN PR=1
770 PRINT " "
780 PRINT "CEILING HEIGHT=";H;" RADIUS=";R;" DET ACT TEMP=";T9;" RTI=";L
790 PRINT " "
800 PRINT " TIME FIRE GAS TEMP DET TEMP"
810 PRINT " sec kW C C"
820 IF PR=0 THEN 920
830 LPRINT "DETACT-QS VERSION 1.1"
840 LPRINT " "
850 LPRINT "CEILING HEIGHT=";H;" m"
860 LPRINT "DETECTOR DISTANCE FROM AXIS OF FIRE=";R;" m"
870 LPRINT "DETECTOR ACTUTATION TEMP=";T9;" C"
880 LPRINT "RTI=";L;" (m*s)^(1/2)"
890 LPRINT " "
900 LPRINT " TIME FIRE GAS TEMP DET TEMP"
910 LPRINT " sec kW C C"
920 I=N-1
930 P=K
940 N=0
950 T4=T1
960 T5=T1
970 T6=T1
980 J=1
990 IF N<S(J+1) THEN 1020
1000 J=J+1
1010 GOTO 990
1020 Q=(N-S(J))/(S(J+1)-S(J))*(Q(J+1)-Q(J))+Q(J)
1030 T4=T5
1040 S6=T6
1050 T6=16.9*Q^(2/3)/H^(5/3)+T1
1060 IF R/H<=.18 THEN 1080
1070 T6=5.38*(Q/R)^(2/3)/H+T1
1080 V6=.95*(Q/H)^(1/3)
1090 IF R/H<=.15 THEN 1110
1100 V6=.2*Q^(1/3)*H^(1/2)/R^(5/6)
```

```
1110 IF V6>.1 THEN 1130
1120 V6=.1
1130 L1=L/V6^.5
1140 B=T6-S6
1150 T5=T4+(S6-T4)*(1-EXP(-1/L1))+B*L1*(EXP(-1/L1)+1/L1-1)
1160 IF P<K THEN 1200
1170 PRINT USING "########.#";N,O,S6,T4
1180 IF PR=1 THEN LPRINT USING "########.#";N,O,S6,T4
1190 P=O
1200 N=N+1
1210 P=P+1
1220 IF T5<T9 THEN 990
1230 GOSUB 1680
1240 PRINT " "
1250 PRINT "        **** DETECTOR ACTUATION AT";
1260 PRINT USING "######.#";E;
1270 PRINT " SECONDS ****"
1280 PRINT " "
1290 IF PR=O THEN 1350
1300 LPRINT " "
1310 LPRINT "        **** DETECTOR ACTUATION AT";
1320 LPRINT USING "######.#";E;
1330 LPRINT " SECONDS ****"
1340 LPRINT " "
1350 PRINT "TYPE A CARRIAGE RETURN TO CONTINUE";
1360 INPUT A$
1370 PRINT " "
1380 PRINT "ANALYZE SAME FIRE WITH DIFFERENT DETECTOR (Y OR N) ";
1390 INPUT A$
1400 IF A$="Y" OR A$="y" THEN 1420
1410 END
1420 PRINT "CHANGE RTI VALUE (Y OR N) ";
1430 INPUT A$
1440 IF A$<>"Y" AND A$<>"y" THEN 1470
1450 PRINT "NEW VALUE = ";
1460 INPUT L
1470 PRINT "CHANGE ACTUATION TEMPERATURE (Y OR N) ";
1480 INPUT A$
1490 IF A$<>"Y" AND A$<>"y" THEN 1520
1500 PRINT "NEW VALUE = ";
1510 INPUT T9
1520 PRINT "CHANGE FUEL TO CEILING HEIGHT (Y OR N) ";
1530 INPUT A$
1540 IF A$<>"Y" AND A$<>"y" THEN 1570
1550 PRINT "NEW VALUE= ";
1560 INPUT H
1570 PRINT "CHANGE RADIUS OF DETECTOR FROM FIRE AXIS (Y OR N) ";
1580 INPUT A$
1590 IF A$<>"Y" AND A$<>"y" THEN 1620
1600 PRINT "NEW VALUE= ";
1610 INPUT R
1620 PRINT "CHANGE PRINTOUT INTERVAL (Y OR N) ";
1630 INPUT A$
1640 IF A$<>"Y" AND A$<>"y" THEN 1670
1650 PRINT "NEW VALUE = ";
```

```
1660 INPUT K
1670 GOTO 770
1680 E=N-1+(T9-T4)/(T5-T4)
1690 E=E*100+.5
1700 E=INT(E)
1710 E=E/100
1720 RETURN
```

NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR-85/3167	2. Performing Organ. Report No.	3. Publication Date July 1985

4. TITLE AND SUBTITLE

Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings

5. AUTHOR(S)

David D. Evans, David W. Stroup

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Recently developed methods to calculate the time required for ceiling mounted heat and smoke detectors to respond to growing fires are reviewed. A computer program, that calculates activation times for both fixed temperatures and rate of rise heat detectors in response to fires that increase in heat release rate proportionally with the square of time from ignition is given. This program produces equivalent results to the tables published in Appendix C, Guide for Automatic Fire Detector Spacing, (NFPA 72E, 1984). A separate method and corresponding program are provided to calculate response time for fires having arbitrary heat release rate histories. This method is based on quasi-steady ceiling layer gas flow assumptions. Assuming a constant proportionality between smoke and heat release from burning materials, a method is described to calculate smoke detector response time modeling the smoke detector as a low temperature heat detector in either of the two response time models.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

ceilings; computer program; egress; escape; fire alarms; fire detection; fire suppression; heat detectors; smoke detectors; sprinkler systems

13. AVAILABILITY

☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

49

15. Price

$8.50

USCOMM-DC 6043-P80